PROPAGATION EFFECTS INFLUENCING THE OBSERVATIONS OF PLANETARY RADIO EMISSIONS

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Abstract

Radio waves suffer several influences when propagating through a medium with a refractive index $n \neq 1$. Far from the source and in the case that geometric optics apply (practicable definition: Variation of n over distances of one wavelength smaller than $\pm 10\%$) the influences can be calculated in a comparatively straightforward way by means of the Eikonal–approximation. For the plasma influence on signal parameters we can distinguish the following 'effects': Absorption which influences predominantly the signal amplitudes, the plasma influence on the length of the phase path which influences carrier phase, the group delay which influences modulation phase, the Faraday effect which influences signal polarization. Various other 'effects' occur if the approximation of geometric optics is not valid of which one case only will be discussed briefly: Scatter processes which lead to amplitude and phase scintillation.

Special attention is given to the Faraday effect which is observed when radio waves propagate through a magneto–plasma. Because of the anisotropy of a magneto–plasma the radio signal has to be split into components having the principal polarizations for which two different refractive indices, n_1 and n_2, are defined (birefringence). Differences in the phase path length for the two components lead to a change of polarization from the source to the receiver. In the simplest case the two principal polarizations are the lefthand and the righthand circular ones and for a signal with linear polarization at the source the Faraday effect gives a rotation of polarization ('Faraday rotation'). More complicated situations will be discussed too. Estimates will be given for the Faraday effect occurring on Jovian Radio Emissions observed from terrestrial stations.

1 Introduction

We have to consider two categories of plasma effects on signal parameters:
a) the influence of refraction and diffraction
b) the influence of random fluctuations of medium properties.

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A straightforward application of the refraction concept is possible only if and insofar the approximation of geometrical optics holds to describe wave propagation. For our purposes this is equivalent with the description of the medium by means of a refractive index (or of refractive indices for the two principal wave components in the birefringence case). Geometrical optics is valid if the refractive index does not change appreciably over distances of one wavelength (it is a high frequency, or better: A short wavelength approximation).

The refractive index n can be considered to define the velocity of phase propagation $v = c/n$ (c: free space velocity of light) for a monochromatic wave (a principal component of a monochromatic wave in the birefringence case).

For an inhomogeneous medium the refractive indices are not constant but they are spatial functions. This implies that in general there exist no analytic solutions for the propagation of monochromatic waves from source to receiver.

Geometric optics is by far the simplest case in the hierarchy of strategies to find an approximate, an iterative or a numerical solution for wave propagation in an inhomogeneous medium. In trying to assess the influence of the atmosphere we discuss refraction effects in the terms of geometrical optics only. We use the 'Eikonal–Ansatz' [see Born and Wolf, 1970] for the formulation of this approximation.

Let $\vec{A}$ be a field quantity of the wave (e.g., electric or magnetic field strength). Then the Eikonal is

$$\vec{A}(\vec{r}) = \vec{A}_o \, \exp\left\{ j \int_{\vec{r}_o}^{\vec{r}} d\vec{r}\, \vec{k}(\vec{r}) \right\}, \qquad j = \sqrt{-1}.$$

The time dependence $\exp(-j\omega t)$ is usually omitted. It could be contained equally well in $\vec{A}_o$. $d\vec{r}$: element of the ray path from the source at $\vec{r}_o$ to the receiver at $\vec{r}$,
$\vec{k}$: phase propagation vector (wave vector); in general $\vec{k}$ is complex.

The direction of the real part is the orthogonal trajectory to the surfaces of constant phase (wave normal), the direction of the imaginary part is the orthogonal trajectory to the surfaces of constant amplitude (in the case that $\vec{A}_o$ is constant).

The magnitude of the real part is proportional to the real part of the refractive index, n: $k_r = (\omega/c)n \quad (\omega = 2\pi\, f;\ f$: frequency of the wave at the source).
The magnitude of the imaginary part is proportional to the imaginary part of the refractive index, $\chi = n\,\kappa$: $\quad k_j = (\omega/c)\chi = (\omega/c)\, n\, \kappa$.

$\vec{A}_o$ includes the 'geometric attenuation' of the amplitude: For a point source $\vec{A}_o$ attenuates with $(1/s_o)$, s_o being the geometrical distance of the receiver from the source. For a plane wave $\vec{A}_o$ would be a constant. (In planetary radio science the assumption of a point source is usually justified. Then the Eikonal describes the wave locally as a plane wave, the real and imaginary parts of $\vec{k}$ defining tangent planes to the curved surfaces of constant phase and amplitude.)

Geometrical optics cannot explain phenomena which arise from rapid changes of the refracting properties of the propagation medium, for example, at boundaries or shadows, in the vicinity of caustics, steep gradients of refractive index. Partial reflection, focusing, diffraction, multipath propagation are among the phenomena which are not described by geometrical optics, at least not in its simple forms. Other cases which cannot be treated with the Eikonal–Ansatz are scattering processes.

The latter lead to case b): The (stochastic) irregularities embedded in the propagation medium induce scattering phenomena which influence the signal parameters.

In general both cases are mixed and it is only a question of the 'strength' of irregularities whether or not the effect of scattering has to be taken into account.

The effect of scattering phenomena is usually described in terms of 'scintillation' of signal parameters (e.g., of amplitude, phase, polarization).

Independent of the receiving system properties we can distinguish two cases of wave propagation through a medium which can be described by adding a stochastic part to a 'regularly varying' refractive index: 1) An 'average' wave surface can be defined on which stochastic phase fluctuations are superimposed; 2) the wave surface is dissolved.

Geometrical optics can be applied for the 'average' wave surface of case 1) only. Fortunately, it is comparatively easy to distinguish case 1) from case 2) for radio waves propagating through the atmosphere of the Earth: The strength of the irregular amplitude fluctuations can be used to set a threshold which ensures that an application system discards case 2) when it occurs.

2 The refractive index for a magneto–plasma and consequences

The starting point is the dispersion formula for a cold magneto–plasma for frequencies substantially higher than the gyrofrequencies of the ions

$$n^2 = 1 - \frac{\tilde{X}(1-\tilde{X})}{1 - \tilde{X} - \tilde{Y}_T^2/2 \pm \sqrt{\tilde{Y}_T^4/4 + \tilde{Y}_L^2(1-\tilde{X})^2}}\,,$$

with $\tilde{Y}_L = \tilde{Y}|\cos\Theta|$ (longitudinal component), $\tilde{Y}_T = \tilde{Y}\sin\Theta$ (transversal component), $\tilde{X} = \dfrac{X}{1+jZ}$, $\tilde{Y} = \dfrac{Y}{1+jZ}$, $j = \sqrt{-1}$. Conventional acronyms: $X = f_p^2/f^2$, $Y = f_g/f$, $Z = \nu/(2\pi f)$, $f_p^2 = (e^2 N)/(4\pi^2 m\epsilon_o) = A\,N$, $f_g = e/(2\pi\ mB)$; f_p: electron plasma frequency, f_g: electron gyrofrequency, ν: effective collision frequency for electrons, f: transmitted frequency, N: electron density, e: electron charge, m: electron mass, ϵ_o: permittivity of free space, B: magnetic flux density. With S.I.–units the value of A is 80.6.

The magnetic field introduces an anisotropy of the medium. The primary consequence is that refractive indices are defined for the 'principal polarizations' only. A signal has to be decomposed into monochromatic partial waves (e.g., by Fourier analysis), and each partial wave has to be split into its 'principal components' having the 'principal polarizations'. In the geomagnetic northern hemisphere of the Earth the + sign in the nominator corresponds to the lefthand elliptical component, the $-$ sign to the righthand elliptical component.

Even the cold magneto–plasma approximation is too complicated for drawing more general conclusions or for deriving 'propagation effects'. First we neglect possible attenuation by neglecting Z (omit the tilde $\tilde{}$) but we note that we have to be careful in cases when attenuation affects one principal component stronger than the other.

We now introduce two border cases, namely the 'quasi–longitudinal' (Q.L.) approximation and the 'quasi–transversal' (Q.T.) approximation. Q.L. neglects the first term under the square root, Q.T. the second.

$$\text{For Q.L. we assume} \qquad \frac{Y_L}{1-X} \gg \frac{Y_T^2}{2} \qquad \text{and gain} \qquad n^2 = 1 - \frac{X}{1 \pm Y_L - Y_T^2/2}$$

for nearly circular principal polarizations.

$$\text{For Q.T. we assume} \quad \frac{Y_T^2}{2} \gg \frac{Y_L}{1-X} \quad \text{and gain} \qquad n_1^2 = 1-X, \qquad n_2^2 = 1 - \frac{X(1-X)}{1-X-Y_T^2}$$

for nearly linear principal polarizations.

If the signal frequency f is 'substantially larger' than the plasmafrequency f_p ($X < 1$) and the gyrofrequency f_g ($Y < 1$), Q.L. is valid for a comparatively wide range of Θ (Table 1). (To gain the limits for Θ replace $\gg$ by a factor of 3.)

Y	X	ϵ
0.014	0.1	1.34°
0.1	0.9025	51.32°

Table 1: Range of Θ for Q.L.: $\Theta = 90° \pm \epsilon$.

2.1 Phase propagation effects in a magneto–plasma

A consequence of the anisotropy of a magneto–plasma is birefringence: The two principal components have different ray paths and the ray paths differ from the wave normals. Snell's law can be applied only for the latter and the ray path has to be constructed step by step which leads to the so–called 'ray tracing' procedures [compare, e.g., Ladreiter and Leblanc, 1990].

For signal frequencies very much higher than both the plasma frequency and the electron gyrofrequency ($X \ll 1$, $Z \ll 1$) one gains a good approximation for signal phase by assuming an 'anisotropic ray path' (= wave normal) and by using $n^2 = 1 - X$. Often a straight line connection from source to receiver is a sufficient approximation for the ray path and the influence of the plasma on the phase of a monochromatic signal component can easily be estimated (**'carrier phase effect'**, sometimes called **'differential Doppler effect'** because the time derivative of phase is frequency). In this simple 'high frequency' approximation it is fairly simple to derive the plasma influence on the phase of a signal modulation: A carrier signal with a sinusoidal amplitude modulation corresponds to three monochromatic partial waves: A carrier and two side waves. Addition of the three partial waves after propagation from source to receiver allows to calculate the plasma influence on the phase of the modulation (**'modulation phase effect'** or **'group delay'**).

Observation of the plasma influence on carrier phase and on modulation phase has to rely on the strong dispersion of the plasma (on the $1/f^2$ dependence of the refractive indices). This means that coherency between signal components is needed. Such coherency does not exist in planetary radio emissions (lack of a 'phase reference') and therefore the carrier phase effect and the modulation phase effect cannot be observed. One should be aware, however, that propagation through a plasma leads to distortions of 'modulations' (e.g., pulses get wider) and to changes in the spectra of complex signals.

2.2 Propagation effects on signal polarization in a magneto–plasma

The plasma influence on signal polarization is left as the only propagation effect readily observable in planetary radio signals. In the Q.L. approximation we can easily follow a monochromatic signal propagating through a magneto–plasma and monitor its polarization: We split the signal into the two circularly polarized components and combine the components again where we are interested in the signal polarization. Each component 'sees' its own refractive index, therefore the phase difference of the two circular components changes continuously which corresponds to a rotation of the signal polarization, usually called 'Faraday–Effect'. Assuming the same ('quasi–isotropic') phase path for the two components (element $\mathrm{d}s_o$) we get for the phase difference

$$\Omega \doteq \frac{2\pi f}{c} \int_S^R \frac{X\, Y_L}{1 - X/2 - Y^2}\, \mathrm{d}s_o \doteq \frac{2\pi f}{c} \int_S^R X\, Y_L\, \mathrm{d}s_o\,.$$

In this approximation a linear polarization of a monochromatic signal remains linear but is rotated about the propagation vector by an angle $\Omega/2$ ('Faraday–Rotation'). Adopting the second approximation we see that Ω depends on $1/f^2$.

When a linearly polarized receiving antenna is used (e.g., an electrical dipole) the Faraday effect on a linearly polarized signal can provide a rotation such that the component of the electrical field strength parallel to the antenna disappears. In this case the signal is lost because the antenna voltage drops to zero ('Faraday null'). Varying plasma properties (e.g., electron density) or ray path variations (relative movement source – receiver) can produce quasi–periodic variations in the received signal strength by means of changes of the amount of Faraday rotation ('Faraday patterns'). With an elliptically polarized signal similar patterns are produced but the signal strength never drops to zero: The signal strength in the 'Faraday null' is the difference in signal strength of the two circular components of the elliptical signal.

The Faraday effect is strongly frequency dependent. Therefore spectrograms show 'Faraday patterns' provided that the monochromatic signals corresponding to the spectral lines are linearly or elliptically polarized and the receiving antenna is linearly polarized. These 'Faraday patterns' appear as a sinusoidal frequency modulation of the line strengths. Using $X = A\, N/f^2$ and $Y_L = (e\, B\, |\cos\Theta|)/(2\pi\, f)$ we get

$$\Omega = \frac{2\pi\, K}{f^2} \int_S^R N\, B\, |\cos\Theta|\, \mathrm{d}s_o\,,$$

and for the frequency derivative we gain

$$\frac{\mathrm{d}\Omega}{\mathrm{d}f} = -\frac{4\pi\ K}{f^3} \int_S^R N\ B\ |\cos\Theta|\ \mathrm{d}s_o\,.$$

As for all other propagation effects on planetary radio signals we can divide the Faraday effect into three parts: 1) The contribution in the Jovian plasma surroundings, 2) the contribution in the interplanetary space, 3) the contribution of the thermal plasma in the surroundings of the Earth (ionosphere and plasmasphere).

Especially for the ionospheric/plasmaspheric contribution it is of advantage to introduce the height element $\mathrm{d}h$ instead of the ray path element: $\mathrm{d}s_o = -\mathrm{d}h/\cos\chi$ ($\mathrm{d}h$: height element, $\chi = \chi(h)$: zenith angle along the ray path). If refraction effects are not too severe it is possible to extract a mean value for $(B|\cos\Theta|/\cos\chi)$ out of the integral and we gain for the contribution of the thermal plasma in the surroundings of the Earth

$$\Omega_3 \ \doteq\ \frac{K}{f^2}\,\overline{\left(\frac{B|\cos\Theta|}{\cos\chi}\right)} \int_0^{h_c} N\ \mathrm{d}h \ =\ \frac{K}{f^2}\,\overline{M}\ N_\perp \ =\ \frac{K}{f^2}\,\overline{M}\ N_m\ \tau\,,$$

and correspondingly

$$\frac{\mathrm{d}\Omega_3}{\mathrm{d}f} \doteq -\frac{4\pi\ K}{f^3}\,\overline{M}\ N_\perp$$

(N_m: maximal (peak) electron density, $\tau = N_\perp\ /\ N_m$: 'equivalent slab thickness').

2.3 Higher order expressions for the Faraday effect

Expanding the difference of refractive indices from the Q.L. approximation leads to

$$n_2 - n_1 = X\ Y_L\left[1 + Y^2 + \frac{1}{2}X \pm \cdots\right] \qquad \text{([ ] complete up to order 4 in } \frac{1}{f}\text{)}.$$

A more general expression which does not rely on the Q.L. approximation is gained by replacing Y_L by

$$\frac{\sqrt{Y_T^4/4 + Y_L^2(1-X)^2}}{(1-X)} \qquad \text{which gives the expansion}$$

$$n_2 - n_1 = X\ Y_L\left[1 + \left(1 + \frac{1}{8}\frac{\sin^4\Theta}{\cos^2\Theta}\right)Y^2 + \frac{1}{2}X \pm \cdots\right] \qquad \text{provided that } X \ll 1.$$

(One should be aware, however, that with increasing $Y_T^2/[2Y_L(1-X)]$ the principal polarizations get more and more elliptical. For $Y_T^2/[2Y_L(1-X)] > 0.8$ or so it makes not much sense to look for a Faraday effect.)

If the [ ] expression is used one should take into account refraction (ray bending) effects as well: If $X \ll 1$ it can be demonstrated at least for the cases of planarly and spherically layered plasmas that the refraction effect on $\int n\ \mathrm{d}s$ is approximately proportional to $1/f^4$ [Leitinger and Putz, 1988, Leitinger, 1991]. The length of the ray path $\int \mathrm{d}s$ itself is influenced by X (influence of order 2 in $1/f$). The calculation of the Faraday effect, however, needs integration of $X\ Y_L$ over the ray path. For planar layering (which is a sufficient approximation for zenith angles $< 60°$) the ray bending can be taken into account quite easily using the ansatz given in Leitinger and Putz, [1988] or in Leitinger, [1991]. The result is the following expression:

$$\Omega \doteq \frac{2\pi f}{c} \int_S^R X\ Y_L \left[1 + Y^2 + \frac{X}{2} + \frac{X}{2}\ \tan^2\zeta\right]\ \mathrm{d}s_o \qquad \text{(complete up to order 5 in } \frac{1}{f}\text{)}.$$

ζ is the zenith angle of the ray. For a spherical Earth it is of course a function of height and it makes sense to take χ, the zenith angle in the 'mean ionospheric height' for the flat Earth ζ.

Extracting mean values for $(B|\cos\Theta|/\cos\chi)$ and for $(B\ Y^2|\cos\Theta|/\cos\chi)$ out of the integral gives for the contribution of the thermal plasma in the surroundings of the Earth

$$\begin{aligned}
\Omega_3 &\doteq \frac{K}{f^2}\left[\overline{M\,(1+Y^2)}\ N_\perp + \frac{A}{2\,f^2}\overline{M}\left(1+\tan^2\chi\right)\ \frac{\eta}{\tau}\ (N_\perp)^2\right] = \\
&= \frac{K}{f^2}\ \overline{M}\ N_\perp\left[\frac{\overline{M\,(1+Y^2)}}{\overline{M}} + \frac{A}{2\,f^2}\left(1+\tan^2\chi\right)\ \frac{\eta}{\tau}\ N_\perp\right] = \\
&= \frac{K}{f^2}\ \overline{M}\ N_\perp\left[\frac{\overline{M\,(1+Y^2)}}{\overline{M}} + \frac{1}{2}\ \frac{f_o^2}{f^2}\left(1+\tan^2\chi\right)\eta\right],
\end{aligned}$$

and correspondingly

$$\begin{aligned}
\frac{\mathrm{d}\Omega_3}{\mathrm{d}f} &\doteq -\frac{4\pi\ K}{f^3}\left[\overline{M\,(1+2\,Y^2)}\ N_\perp + \frac{A}{f^2}\overline{M}\left(1+\tan^2\chi\right)\ \frac{\eta}{\tau}\ (N_\perp)^2\right] = \\
&= -\frac{4\pi\ K}{f^3}\ \overline{M}\ N_\perp\left[\frac{\overline{M\,(1+2\,Y^2)}}{\overline{M}} + \frac{A}{f^2}\left(1+\tan^2\chi\right)\ \frac{\eta}{\tau}\ N_\perp\right] = \\
&= -\frac{4\pi\ K}{f^3}\ \overline{M}\ N_\perp\left[\frac{\overline{M\,(1+2\,Y^2)}}{\overline{M}} + \frac{f_o^2}{f^2}\ \left(1+\tan^2\chi\right)\eta\right]
\end{aligned}$$

($\eta = (\tau \int_S^R N^2\ \mathrm{d}h)/(\int_S^R N\ \mathrm{d}h)$ is a 'shape factor' for the electron density – height distribution. A uniform layer gives $\eta = 1$, a triangular layer gives $\eta = 2/3$. A realistic estimate is $\eta = 0.7 \pm 0.15$ for mid latitudes (compare, e.g., Leitinger, [1990]). f_o: maximal plasma frequency ('critical frequency' foF2) of the ionosphere).

If the electron content is not known but suitable ionosonde data are available it is of advantage to use critical frequency instead of electron content and sometimes it is better to use expressions containing Y instead of expressions containing M. For this case the formulae read as follows

$$\Omega_3 \doteq \frac{2\pi f}{c}\ \overline{Y|\cos\Theta|/\cos\zeta}\ \frac{f_o^2}{f^2}\ \tau\left[\frac{\overline{(Y|\cos\Theta|/\cos\zeta)(1+Y^2)}}{\overline{Y|\cos\Theta|/\cos\zeta}} + \frac{1}{2}\ \frac{f_o^2}{f^2}\left(1+\tan^2\chi\right)\eta\right],$$

and

$$\frac{\mathrm{d}\Omega_3}{\mathrm{d}f} \doteq -\frac{4\pi}{c}\,\overline{Y|\cos\Theta|/\cos\zeta}\,\frac{f_o^2}{f^2}\,\tau\left[\frac{\overline{(Y|\cos\Theta|/\cos\zeta)(1+Y^2)}}{\overline{Y|\cos\Theta|/\cos\zeta}}+\frac{f_o^2}{f^2}\left(1+\tan^2\chi\right)\eta\right].$$

The second correction term can be substantial: A nighttime critical frequency of 6 MHz (which is a quite normal mid latitude value for high solar activity) gives for $f = 20$ MHz, for $\chi = 60°$, and for $\eta = 0.7$ a correction term of $f_o^2/(2\,f^2)\;(1+\tan^2\chi)\eta = 0.126$. Since in the atmosphere of the Earth everywhere $f_g < 1.74$ MHz the influence of Y^2 is only small: For a European mid latitude station observing Jupiter $\overline{f_g}$ is around 1 MHz which leads to $\overline{Y^2} \doteq 0.0025$ for a signal frequency of 20 MHz.

It is important to note that one can gain a good estimate for $\overline{M}$ and for the other mean values by taking the actual value in the 'mean ionospheric height' h_i which is to be found in the vicinity of the height of the first momentum of the electron density distribution for the ionosphere ('center of gravity' of the ionospheric electrons). A fixed height of $h_i = 400$ km is a good estimate for most purposes. Titheridge [1972] has shown that for the Faraday effect on the signals of geostationary satellites and for the given choice of h_i, $N_\perp$ should be interpreted to be the electron content from the ground up to a height of 2000 km. Our own model calculation confirm approximately this finding for ray paths from Jupiter to a mid latitude receiving station. Titheridge [1972] found accuracy limits of ±5% for $N_\perp$, for Jupiter signals it is probably safer to take ±10%. (This does not include experimental errors nor refraction effects, it includes the influence of the plasmaspheric electrons only. Their influence is small because above 2000 km B_L decreases quickly with height.)

Table 2 gives examples for Faraday rotation values obtained with a ray path which arrives at Graz (47.08°N, 15.45°E) with a zenith angle of 45° and from the south (azimuth = 180°). In 400 km ('ionospheric point', 43.77°N, 15.45°E) the zenith angle is $\chi = 41.89°$ and $\cos\chi = 1.34324$, $B = 38805$ nT, $B_L = 37968$ nT, $f_g = 1.086$ MHz, $f_g|\cos\Theta| = 1.063$ MHz. The geomagnetic quantities have been calculated by means of the International Geomagnetic Reference Field (IGRF) 1980.

Table 2: Faraday rotations $(\Omega_3)/(2\pi) = [(\Omega_3)_1]/(2\pi) + [(\Omega_3)_2]/(2\pi)$, $(\Omega_3)_1$ is this part which depends on $(1/f^2)$, $(\Omega_3)_2$ is that part which depends on $(1/f^4)$.

f MHz	f_o MHz	τ km	$N_\perp$ 10^{15} m^{-2}	$[(\Omega_3)_1]/(2\pi)$	$[(\Omega_3)_2]/(2\pi)$
15	2	300	14.9	19.0	0.21
15	4	300	59.6	76.0	3.39
15	4	500	99.3	126.7	5.66
15	6	300	134.0	171.0	17.19
30	2	300	14.9	4.7	0.01
30	4	300	29.8	18.9	0.21
30	4	500	99.3	31.5	0.35
30	6	300	44.7	42.6	1.07

3 Data sources for the terrestrial Faraday effect

For ionospheric data needed to assess the terrestrial Faraday effect on planetary radio signals we have essentially the following sources (in order of decreasing usefulness):

1. Electron content measured by means of the Faraday effect on the VHF signals of geostationary satellites,

2. Electron content measured by means of the Differential Doppler effect on the signals of polar orbiting satellites,

3. Peak electron density from ionosonde measurements.

Electron content from the Faraday effect on signals of geostationary satellites has the advantage that it can be reconverted easily into Faraday rotation data which are realistic for low elevation ray paths. For high elevation ray paths, however, the data have to be adjusted. This is not too easy a task because for good accuracy one needs information about the dependence of actual electron content on latitude and longitude. This information has to be taken from other sources, or from models, or from 'past experience'. (Geostationary satellites provide fixed ray paths, therefore one gains good information about the time dependence but no information about the spatial dependence.) Unfortunately the VHF beacons on geostationary satellites are faded out because these beacons are no longer needed for station keeping or other purposes.

Polar orbiting satellites with suitable dual frequency coherent radio beacons are used to gain the latitude dependence of ionospheric electron content. With the satellites of the US Navy Navigation System (NNSS) the temporal resolution is moderate: There are 5 to 7 satellites in operation providing about 10 to 15 useful passes a day for a mid latitude receiving station. The passes are distributed irregularly. It is recommended to combine the observations of two or more receiving stations to gain good values for the 'initial phase difference' [Leitinger et al., 1975, Leitinger and Putz, 1978]. In most cases 'scaling' of electron content to the ray path for planetary radio signals is possible with fairly good accuracy. The NNSS satellites, however, provide electron content only up to about 1000 km.

In the future the US Global Positioning System (GPS) could provide electron content for Faraday assessment provided that some calibration problems are overcome and provided that the system is not degraded for the unprivileged user. The GPS satellites are in 12 hour orbits (height around 20000 km) and in observations of one satellite only time dependence is coupled with latitude and longitude dependence. Therefore all visible GPS satellites should be observed simultaneously and the data from several receiving stations should be combined to gain a good impression of the temporal and spatial behavior of the electron content. Then 'scaling' to a specific ray path would be no difficulty. There is an inherent problem with GPS data: Essentially they are the sum of ionospheric plus plasmaspheric electron content. For Faraday assessment the ionospheric electron content is needed because the electrons above about 2000 km contribute only negligibly. The separation problem could be severe during nighttime: The experiences from the so–called

ATS–6 Radio Beacon Experiment [Davies et al., 1976, Davies, 1980] are that for low solar activity the average nighttime plasmaspheric electron content can be 40% of the ionospheric content. This percentage is by no means fixed: The relative plasmaspheric content is highly variable (it is lower after a geomagnetic storm, etc., compare e.g., Degenhardt et al., 1977, Joshi et al., 1984). The percentage for high solar activity is simply not known. Model calculations indicate that it could be higher than 40%.

Peak electron density from ionosonde measurements could be used when combined with the equivalent slab thickness of the ionosphere, τ: Electron content is peak electron density times slab thickness. The primary ionosonde information is F–layer critical frequency foF2 (called f_o in the formulae of Chapter 2). Conversion formula: $N_m = f_o^2/80.6$ (f_o in Hz, N_m in m^{-3}) or electron content $N_\perp = (f_o^2/80.6)\ \tau$ (τ in m gives $N_\perp$ in m^{-2}). Since in Europe the ionosonde network is still comparatively dense interpolation processes can give fairly good foF2 for the geographic location of the 'ionospheric point' on the ray path for planetary radio signals. In other regions of the world the situation is much worse. The problem is to make a good guess for the equivalent slab thickness, τ. For winter midnight and mid latitudes Liu and Davies [1990] give $\tau = 260$ km for low solar activity and $\tau = 270 \ldots 350$ km for high solar activity. These are 'typical' values. One should account for a nighttime variability of at least ± 50 km around the values given. The critical time for slab thickness is the time around sunrise when τ has high but strongly variable values [Liu and Davies, 1990, Huang, 1983].

For high accuracy it is strongly recommended to combine all available information about the F–layer of the ionosphere. Then it should be possible to calculate the terrestrial Faraday effect on planetary radio signals with a relative accuracy of about $\pm 20\%$ provided that X_o is not larger than about 0.1. Higher accuracy is unrealistic because of the scaling and calibration problems involved. This author is convinced that it would be difficult to prove a relative accuracy of, say, $\pm 10\%$. On top of calibration and scaling problems one would have to deal with inaccuracies from ionospheric dynamics, e.g., from the action of atmospheric gravity waves [compare, e.g., Leitinger and Putz, 1991].

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